Eccentricities of Flow - Elliptic Flow Fluctuations and Evidence for Transverse Localization in the Initial State of the Matter in Relativistic Heavy Ion Collisions[*]

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Abstract　Recent measurements of event-by-event elliptic flow in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200\mathrm{GeV}$ exhibit large relative fluctuations of about 40%—50%. The data are well described by fluctuations in the shape of the initial collision region, as estimated event-by-event with the participant eccentricity using Glauber Monte Carlo. These results, combined with the demonstrated participant eccentricity scaling of the elliptic flow across nuclear species, constitute evidence of transverse granularity in the initial matter production in these collisions.

Key words　elliptic flow, fluctuation, event-by-event

1　Introduction

Elliptic flow (v_2) is one of the key observables in the understanding of the dynamics of heavy ion collisions. The observation of a significant azimuthal anisotropy in the momentum and/or spatial distributions of the detected particles relative to the reaction plane, is direct evidence of interactions between the

initially produced particles in heavy ion collisions. These interactions must occur at relatively early times, since expansion of the source rapidly reduces the magnitude of the spatial asymmetry.

Typically, the connection between the initial and final-state anisotropy is provided by hydrodynamical models that relate a given, initial source shape to the distribution of produced particles. In such calculations, it is common to use smooth, event-averaged, initial conditions. However, event-by-event fluctuations in the shape of initial interaction region must not be neglected. As a means to quantify the effect of initial-state eccentricity fluctuations, PHOBOS has introduced the "participant eccentricity" [1, 2],

$$\epsilon_{\text{part}} = \frac{\sqrt{(\sigma_{yy}^2 - \sigma_{xx}^2)^2 + 4\sigma_{xy}^2}}{\sigma_{yy}^2 + \sigma_{xx}^2},$$

where $\sigma_{ab}^2 = \langle ab \rangle - \langle a \rangle \langle b \rangle$ are the per-event (co-) variances of the participant nucleon position distributions in the transverse plane. The magnitude and shape of ϵ_{part} as a function of centrality were found to be robust to variations of the Glauber parameters.

Fluctuations in the shape of the initial state interaction region might be expected to be more pronounced for smaller species and for more peripheral events. This is borne out by the data, where a striking agreement between the elliptic flow signals in Cu+Cu and Au+Au data as a function of centrality is obtained when scaled by the participant eccentricity, $v_2/\langle \epsilon_{\text{part}} \rangle$[1, 2]. The agreement is not as good when scaled by the commonly used eccentricity, $\varepsilon = \dfrac{\sigma_y^2 - \sigma_x^2}{\sigma_y^2 + \sigma_x^2}$, that does not take into account initial state fluctuations.

Given the obvious importance of fluctuations in the initial state to the final elliptic flow measurement, PHOBOS recently developed a new technique to measure dynamical flow fluctuations in our data[3, 4]. The new analysis and results stemming from it are summarized below.

2 Elliptic flow fluctuations analysis technique and results

The PHOBOS flow fluctuations analysis extracts the flow signal, event-by-event, from data in the PHOBOS multiplicity array which detects a very large fraction of the produced particles over the pseudorapidity range $|\eta| < 5.4$[5]. The event-by-event measurement is done using a maximum likelihood fit with two parameters to the hit information over the full acceptance of pseudorapidity. The parameters determined in the maximum likelihood fit are the observed elliptic flow at midrapidity, $v_2(0)$, and the reaction plane angle, ϕ_0^{obs}. The pseudorapidity dependence in the likelihood fit, $v_2(\eta)$, is parametrized with a triangular shape, $v_2^{\text{tri}}(\eta) = v_2 \left(1 - \dfrac{|\eta|}{6} \right)$, or alternatively with a trapezoidal shape,

$$v_2^{\text{trap}}(\eta) = \begin{cases} v_2 & \text{if} \quad |\eta| < 2 \\ \dfrac{3}{2} v_2^{\text{tri}}(\eta) & \text{if} \quad |\eta| > 2 \end{cases},$$

where $v_2 \equiv v_2(0)$. Both parametrizations yield good descriptions of the previously measured (mean) $v_2(\eta)$ shapes[6]. The fit includes a probability density function that corrects for non-uniformities in the acceptance of the used sub-detectors.

In order to disentangle known (mostly statistical) from unknown (dynamical) contributions to the measured flow fluctuations, a detailed knowledge of the detector response is required. A response function, $K(v_2^{\text{obs}}, v_2, n)$, is defined as the distribution of the event-by-event observed elliptic flow, v_2^{obs}, for events with constant input flow value, v_2, and multiplicity, n. This response function is designed to account for detector deficiencies, as well as for multiplicity and finite-number fluctuations when mapping the true distribution of v_2 to the distribution of v_2^{obs}. If $f(v_2)$ is the true v_2 distribution for a set of events in a given centrality class, $f(v_2)$ is related to the distribution of v_2^{obs}, $g(v_2^{\text{obs}})$, by

$$g(v_2^{\text{obs}}) = \int K(v_2^{\text{obs}}, v_2, n) f(v_2) N(n) \, \mathrm{d}v_2 \, \mathrm{d}n, \qquad (1)$$

where $N(n)$ is the multiplicity distribution of the events in the given set of events.

To obtain the kernel in bins of v_2 and n with enough precision, would require on the order of 100 million MC events. Instead the kernel can be parametrized, allowing the use of about 1.5% of that statistics to reach the required precision. For a per-

fect detector, the response is given by Eq. (A13) from Ref. [7] (with $\alpha \to v_2^{\mathrm{obs}}$, $\overline{\alpha} \to v_2$ and $M \to n$). In practice, however, it turns out that v_2 is suppressed, with the suppression dependent on n, and that the resolution (σ) has a constant background contribution. With $v_2^{\mathrm{sup}} = (An+B)v_2$ and $\sigma = C/\sqrt{n}+D$, this leads to

$$K(v_2^{\mathrm{obs}}, v_2, n) = \frac{v_2^{\mathrm{obs}}}{\sigma^2} \exp\left(-\frac{(v_2^{\mathrm{obs}})^2 + (v_2^{\mathrm{sup}})^2}{2\sigma^2}\right) \times$$
$$I_0\left(-\frac{v_2^{\mathrm{obs}} v_2^{\mathrm{sup}}}{\sigma^2}\right), \qquad (2)$$

where I_0 is a modified Bessel function. The four unknown parameters (A, B, C, D) are obtained using the modified HIJING samples.

In order to determine the mean and variance of the true v_2 distribution, $f(v_2)$, and extract the fluctuations, we assume a Gaussian distribution for $f(v_2)$, with two parameters, $\langle v_2 \rangle$ and σ_{v_2}. For given values of $\langle v_2 \rangle$ and σ_{v_2}, it is possible to take the integral in Eq. (1) to obtain the expected distribution, $g_{\exp}(v_2^{\mathrm{obs}}|\langle v_2 \rangle, \sigma_{v_2})$. By comparing the expected and observed distributions, the values for $\langle v_2 \rangle$ and σ_{v_2} are found by a maximum likelihood fit.

The analysis chain is applied to the $\sqrt{s_{\mathrm{NN}}} = 200\mathrm{GeV}$ Au+Au data set from Run 4 in bins of centrality. The results ($\langle v_2 \rangle$ and σ_{v_2}) are obtained separately for triangular and trapezoidal $v_2(\eta)$ shape and averaged over 10 bins of collision vertex (2cm width). The systematic errors (all sources added in quadrature) are estimated by including variations from different vertex and ϕ_0^{obs} bins and changes introduced by the triangular and trapezoidal $v_2(\eta)$ shapes. Since the functional form of the true distribution is unknown, also differences arising from a flat rather than a Gaussian ansatz for $f(v_2)$ are included. Furthermore, we have performed extensive studies of the analysis response to MC samples, prepared to match the observed multiplicity distribution and $\langle v_2 \rangle$, in bins of centrality and known input values of fluctuations (including zero). The discrepancies of the obtained to the input fluctuations in the vicinity ($\pm 20\%$) of the measured values per centrality bin are an additional source of the systematic error. Their con-

tribution becomes increasingly important for lower values of v_2, which is the dominant reason to exclude the 0—6% most central bin from the analysis. Fig. 1 shows the mean flow results obtained with the event-by-event analysis projected to mid-rapidity by $\langle v_2 \rangle = 0.5\left(\dfrac{11}{12}\langle v_2^{\mathrm{tri}} \rangle + \langle v_2^{\mathrm{trap}} \rangle\right)$, which agree well, within scale errors, with the published results of the event-averaged sub-event based technique using hits or tracks[6]. This constitutes an important, completely independent verification of the event-by-event analysis. Fig. 2 presents the relative flowfluctuations, $\sigma_{v_2}/\langle v_2 \rangle$. In the ratio most of the forementioned systematic errors scale out. Large relative fluctuations of about 40%—50% are observed, with relative little centrality dependence. The PHOBOS results presented here are consistent with a recent, preliminary measurement of elliptic flow fluctuations by the STAR collaboration[8].
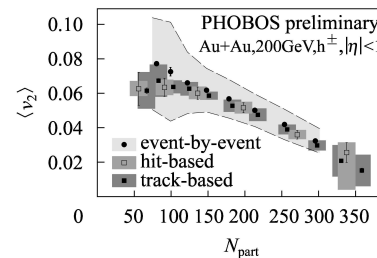

Fig. 1. Mean flow, $\langle v_2 \rangle$, as a function of centrality, for $\sqrt{s_{\mathrm{NN}}} = 200\mathrm{GeV}$ collisions at mid-rapidity, measured by the event-by-event analysis, compared to the published results obtained with the event-averaged, sub-event based technique using hits or tracks[6].
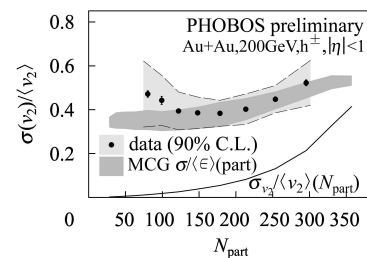

Fig. 2. Relative flow fluctuations, $\sigma_{v_2}/\langle v_2 \rangle$, as a function of centrality, for $\sqrt{s_{\mathrm{NN}}} = 200\mathrm{GeV}$ collisions at mid-rapidity, compared to the prediction, $\sigma_\epsilon/\langle \epsilon \rangle$, from the participant eccentricity, and to an estimate of N_{part} induced fluctuations using a fit of $\langle v_2 \rangle(N_{\mathrm{part}})$.

3 Fluctuations expected from the participant eccentricity model

The participant eccentricity picture accounts for nucleon-position fluctuations in the participating nucleon distributions by calculating the eccentricity, event-by-event, with respect to the principal axes of the overlap ellipse in a MC Glauber (MCG) simulation. In a hydrodynamical scenario, such fluctuations in the shape of the initial collision region would lead naturally to corresponding fluctuations in the elliptic flow signal. To estimate their magnitude, it is assumed that $v_2 \propto \epsilon$ event-by-event. This leads to $\sigma_{v_2}/\langle v_2 \rangle = \sigma_\epsilon/\langle \epsilon \rangle$, where σ_{v_2} (σ_ϵ) is the standard deviation of the event-by-event distribution v_2 (ϵ), provided there are no other sources of elliptic flow fluctuations. Neglecting all other sources of elliptic flow fluctuations, the participant eccentricity MCG simulation predicts relative fluctuations ($\sigma_{v_2}/\langle v_2 \rangle$) of 35%—50% in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$GeV. The prediction is shown in Fig. 2 as a function of N_{part}. The data are well described by the prediction, $\sigma_\epsilon/\langle \epsilon \rangle$, from the participant eccentricity obtained in MCG simulations (to determine the 90% confidence level band shown in Fig. 2, the Glauber parameters were varied within reasonable limits as described in

Ref. [2]). The contribution from N_{part} fluctuations, estimated using a fit to the $\langle v_2 \rangle$ data and the known N_{part} distributions from the PHOBOS centrality trigger studies, is neglible in the measured centrality range.

4 Conclusions

Recent results on event-by-event elliptic flow fluctuations in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 200$GeV exhibit large relative fluctuations of about 40%—50%, relatively independent of centrality. The new data are well described by fluctuations in the shape of the initial collision region, as predicted with the participant eccentricity using MCG simulations.

These results substantiate conclusions from previous studies by PHOBOS on the relevance of such event-by-event fluctuations for the elliptic flow across nuclear species. The initial-state geometry seems to drive the hydrodynamic evolution of the system, not only on average, but event-by-event. The success of the participant eccentricity model in describing both the geometric scaling and fluctuations of the elliptic flow is consistent with the matter present in the initial stage of relativistic heavy ion collisions being created with a transverse granularity similar to that of the participating nucleons.

References

1 Manly S et al. (PHOBOS). NPA, 2006, **774**: 523—526
2 Alver B et al. (PHOBOS). Submitted to PRL, 2006, nucl-ex/0610037
3 Alver B et al. (PHOBOS). 2006, nucl-ex/0608025
4 Loizides C et al. (PHOBOS). 2006, nucl-ex/0701049
5 Back B B et al. (PHOBOS). NPA, 2005, **757**: 28
6 Back B B et al. (PHOBOS). PRC, 2005, **72**: 051901(R)
7 Sorensen P et al. (STAR). 2006, nucl-ex/0612021
8 Ollitrault J Y. PRD, 1992, **46**: 229